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THE MAGNETOSTRICTION OF SPECIMENS OF NICKEL AND INVAR AS A FUNCTION OF TENSION

by

Caddie Gertrude George

A Thesis Submitted for the Degree of
Bachelor of Philosophy
Normal Course

University of Wisconsin

1922

6873362

Several investigators have made careful measurements of the elongation of various metals due to the magnetic fields in which they were placed. The alteration of the dimensions of a body due to magnetization is called magnetostriction. This paper is the result of observations of the magneto striction of a specimen of pure nickel and a specimen of invar.

The question of magneto striction in reversible nickel steels is important in the construction of scales of extreme accuracy and in instruments where measurements must be exceedingly accurate for considerable load. Even the field of the earth makes a slight change in the dimensions of a metal holding up a load. The chief alteration of dimensions, however, is the one due to the magneto strictive effect caused by temperature variations, this being larger, but not to be confused with thermal expansion.

It was impossible, in the time taken to make the observations given here, to obtain data from which to make general statements on the subject, so the papers prepared by others working along the same line will be drawn upon for further evidence. Little was done before 1900 on this magnetic effect. The College of Science of Tokyo, Japan, has given us more than any other institution through the papers in its Journal written on the subject by H. Nagaoka, Professor of Physics, and K. Honda and S. Shimizu, instructors in Physics.

The metals used have been both in the form of ovoids and rods, but the results are the same. If the induction increases when the wire is stretched, the length of the wire increases when it is magnetized, and vice versa. R. A. Houston expressed

this in the equation (1)

$$\frac{v \, \delta B}{4\pi \, \delta F} = \frac{\delta x}{\delta H}$$

where: v = Volume of specimen.
B = Induction in wire.
F = Stretching force.
x = Vertical displacement of lower end of wire.
H = Intensity of magnetic field

Then, dealing with nickel and iron, $B = 4\pi I$ and the above equation becomes

$$\frac{v \, \delta I}{\delta F} = \frac{\delta x}{\delta H} \qquad \text{or} \qquad \frac{\delta I}{\delta p} = \frac{\delta a}{\delta H}$$

if: a = Elongation per unit length.
p = Stretching force per unit area of cross section.

Working with iron-carbon alloys, Herbert G. Dorsey(2) found that the maximum elongation decreases with the carbon content to 0.9% carbon, then increases. The magneto striction of his specimens depended upon their previous history. Steels slowly cooled had greater elongation and susceptibilities than those that had been quenched. These rods gave different values for different lengths of the same quality of iron and showed greater percentage elongation in the middle of a rod than for the entire rod.

Guillaume also discovered that cold drawing and quenching lower the expansibility at ordinary temperatures, and that annealing raises it. From this it is apparent that, where it is desired to get rid of magnetic expansion, it is well to use 25% content of nickel or unannealed wire.

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(1) Philosophical Magazine, Vol.21, Jan.1911, p7.
(2) Physical Review, Vol.30, 1910, pp 698-719.

As early as 1847, Joule(1) published the results of investigations of the effect of tension on magnetic elongation, and these results were substantiated by S. Bidwell(2) in 1886. Bidwell found that tension diminishes the magnetic elongation of iron, causes the magnetic contraction to take place with a smaller magnetizing force, and increases the contraction in strong fields. These changes become greater as the tension is increased. For nickel, the magnetic contraction is diminished by tension in weak fields, but is increased in strong fields, these changes increasing with the tension. Later the same results were obtained by B. Brackett, 1897, G. Klingenbert, 1897, and K. Taugl, 1901.

S. R. Williams(3) came to the conclusion that the vertical field of the earth is effective in the case of nickel but is negligible with steel; however, the effect is so small, less than the magnitude of 10^{-7}, that it was not considered in the data given here.

Nickel steel has enormous volume change compared with iron or nickel, and because of this and its extensive use in all kinds of work, it has been experimented upon considerably over a wide range of percent alloys. The rate of increase of length has been found to diminish as the percentage of nickel increases, pure nickel showing a contraction. The 25% nickel alloy shows no change of length, at least none that can be measured by the arrangements used. This is similar to the magnetization of

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(1) Philosophical Magazine, Vol.30,1847, pp 76,225.
(2) Proceedings of Royal Society, Vol.40, 1886, pp 109,257.
(3) Physical Review, Vol.10, Aug.1917, pp 129-139.

nickel steel, as the 25% alloy has the minimum susceptibility. However, the relation does not hold with all alloys, as, for instance, 29.2% nickel has the maximum susceptibility but not the maximum elongation. The elongation of nickel steels in high fields becomes asymptotic as the percent of nickel is increased to 46%(1). Maximum elongation takes place in weak fields as the quantity of nickel increases. All nickel steels indicate increased length in fields not exceeding 2000 gausses(2). There is a point representing a certain field in the curve of elongation of every nickel steel alloy where the direction is quite sharply inflected and after which the increase in length is more gradual and at a more constant rate.

Another strange result noticed is that 29% nickel offers the least resistance to breaking but when the stress applied is very close to that required for breaking the elongation is maximum(3). The effect of elongating nickel steel by applying tension is to increase the magnetization.

The effects previously shown had been due to direct current fields, so W. Brown(4) subjected soft nickel wire to low alternating fields while sustaining a small load, with the result that greater contraction was caused by the alternating than by the direct current field. This difference was 63% greater for the smallest load used, down to 44% for the largest load.

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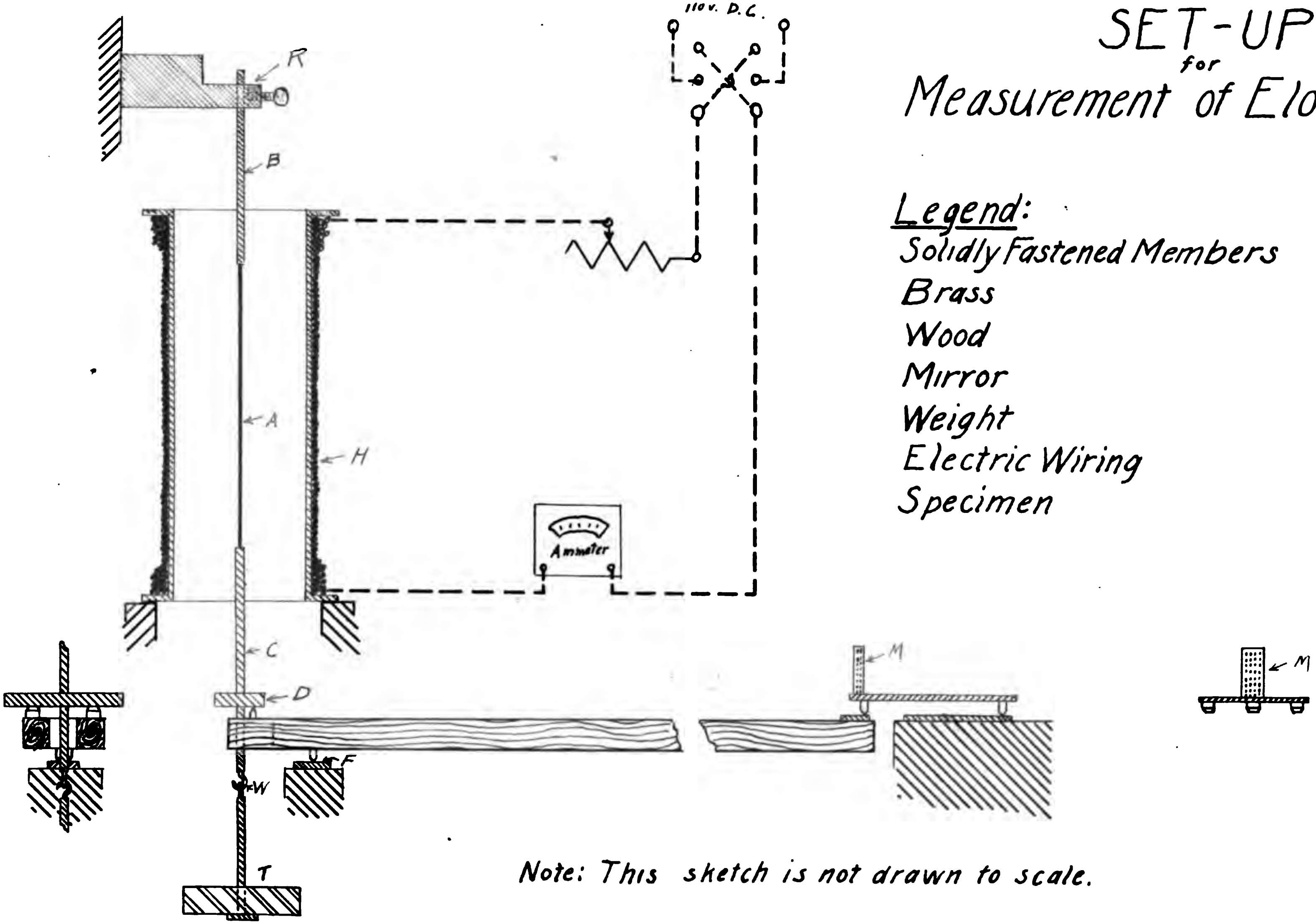
(1) Nagaoka and Honda, Tokyo Math.-Phys. Soc.Proc., 1905, p 9.
(2) Nagaoka and Honda, Jour.of College of Sc.,Tokyo, Vol.16, 1901-1903, Article 8.
(3) Nagaoka and Honda, Tokyo Math.-Phys. Soc.Proc., 1905, p 9.
(4) Royal Dublin Society Proc., Vol.14, May,1914, pp 297-301.

SET-UP for Measurement of Elongation



Legend:

Solidly Fastened Members	▨
Brass	▨
Wood	▨ or ▤
Mirror	▦
Weight	▨
Electric Wiring	– – – –
Specimen	——

Note: This sketch is not drawn to scale.

The change of the modulus of elasticity in ferromagnetic materials due to magnetization can account for but a very small part of the total elongation, that due to the stretching produced by the load being omitted from the readings by putting the weights on before producing the field. (1) In nickel the elasticity decreases in weak fields and increases in strong. In weak fields, the rate of decrease diminishes as the load is increased; in strong fields, however, the contrary is the case.

Several theories have been advanced to explain magneto striction and it is evident that they are all connected with the process of magnetization. C. Barus(2) and S. Bidwell(3) base their explanation of the phenomenon on the rotation of the molecular magnets. Eving's theory of magnetic induction is said by D. Hurmuzeseu(4) to be the explanation. S. R. Williams(5) ascribes the effect to the presence of intrinsic fields brought about by the varying orientation of the molecular magnets.

The first specimen used was a rod of chemically pure nickel which had been drawn to a uniform diameter. The wire was shorter than the solenoid in which it was hung and the ends were soldered into rods of brass of larger diameter, brass being used because it is not affected by the magnetic field. The accompanying diagram illustrates the specimen when ready to be placed in the field of the solenoid. A is the specimen be-

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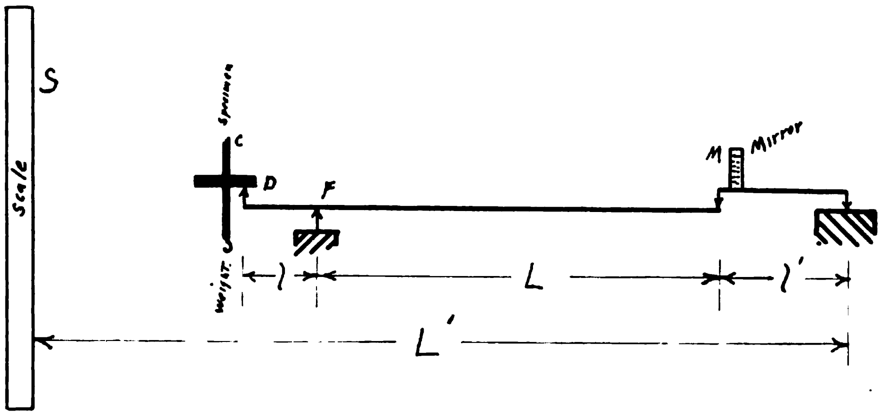
(1) Honda, Shimizu, and Kusakabe, Jour. Coll.of Sc.Tokyo, Vol.16, 1901-1903, Article 12.
(2) National Acad.Science Proc., Vol.5, 1919, pp 267-272.
(3) Phys. Rev., Vol.10, 1917, pp 129-139.
(4) Rev.Gen.d'El.,Vol.4, Aug.1918, pp 211-214.
(5) Phys. Rev., Vol.10, 1917, pp 129-139.

tween the brass rods B and C . D is a piece of Brass 6.5 mm. in thickness, which was soldered to C to serve as the means of transmitting the force due to elongation to the first lever of the measuring system. The weights used for the various tensions were hung from the hook W at the end of the rod C . All the specimens were prepared in the same manner.

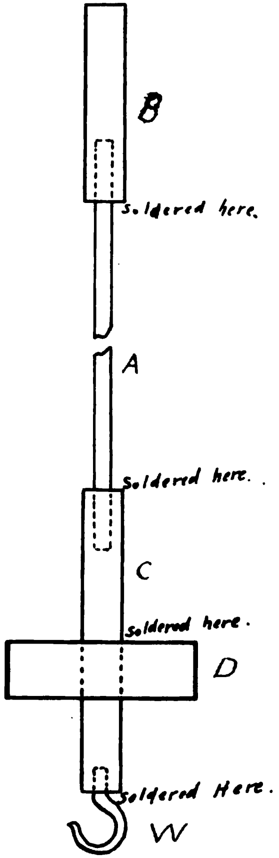
The specimen was hung from a cross rod so that it hung inside the solenoid H coaxial with the coil. End effects were avoided by having the wire shorter than the solenoid. The solenoid was 40 cm. long, wound on a brass tube 6 cm. in diameter. There were seven layers of #12 copper wire, and at each end there were two additional layers 5 cm. and 2 cm. long to secure a more uniform field. The solenoid was one that had been made for use by Butler and Cook in preparing a Master's thesis in 1919 on "The Effect of a Magnetic Field upon the Resistance of Iron", and the description of it is taken from their thesis. The field on the axis at a distance of 10 cm. from the center was 0.53% less than at the center. The field as computed from the dimensions of the solenoid was found to be 35.41 I where I is the current in amperes. The field in the solenoid was produced by direct current at a potential of 116 volts, a rheostat being used in series with the generator to control the current, fifteen amperes being the largest current used. The field was calculated by using the constant 35.41 times the current.

The elongation was measured by a system of levers which magnified the effect so that it could be read with considerable

Details of Set-Up



Schematic
of
Optical Lever



Mounting
of
Specimen

Note: Neither of the above sketches are to scale.

accuracy, the system being changed to produce greater magnification for the invar than for the nickel. The load T caused the plate D to support the wooden lever by bearing down on l which rested on a fulcrum F . An expansion would cause l to lower and L to rise which in turn moved the optical lever l' on which a mirror was fastened. In order to increase the magnifying power of the system the scale S was placed at a distance of about 200 cm. from the mirror and back of the observer. This location facilitated the manipulation of the rheostat and key, while taking the readings through a telescope, the cross-hairs of which were focused on a zero point of the scale reflected by the mirror. The distance L' from the stationary support of the optical lever to the scale served as the other part of the l' lever system. The magnifying power M of the first system is given by

$$M = \frac{L}{l}$$

and of the second system, by

$$M' = \frac{L'}{l'}$$

Hence, the total magnifying power M_t was

$$M_t = M\,M'$$

The reciprocal of this value gave the actual value of unit deflection read by the shifting of the scale with reference to the cross-hair.

As slight vibrations of the building due to running motors, high winds, and banging doors caused prolonged vibration of the lever system which made observations impossible, a sheet of zinc was suspended from the outer end of L into a vessel of water

which served as a damping agent.

In order to prevent the Wiedemann or torsion effect which would have caused the lever 1L to rotate and disturb 1' , a very fine wire was put through the outer end of L and extended horizontally to either side at right angles to the lever and fastened securely. The wire did not prevent the vertical movement of the lever as it was not taut. The sensibility was such that an elongation as small as 0.0002 mm. was plainly discernible.

The observations were taken by first putting on a small load, allowing it to stand for a couple of hours until it had stretched the wire as much as it would. Then the switch was closed, passing a small current through the circuit. The reading was taken at once and then the switch opened so that there would be as little heating of the coil as possible. This was especially necessary for large currents, but the temperature in no instance rose more than a few degrees, so the thermal expansion was negligible. Then the specimen was demagnetized by changing the direction of the current rapidly by means of the reversing switch. After several reversals, and with the switch open, the apparatus would usually return to the zero reading of the previous trial, and if, due to slipping of some part of the apparatus, the same zero reading was not obtained the second value of the deflection S taken for the same current would be equal to the first. The readings for each field strength were taken at least two times to eliminate error, and the system was demagnetized after each reading. The fields were increased to

avoid any effects due to residual magnetism, then when a run was completed with a given tension on the specimen the load was increased, always waiting for at least a half hour for the weight to complete stretching the wire. The two heaviest loads were not used until after the weights up to eight kilograms had been run several times because of the danger of reaching the limit of elasticity for the specimen. The wires were allowed to rest a few days under little tension after using high fields and loads so that they might lose any magnetism that remained and contract to the original length. The specimens had been aged for at least a few months before using which caused them to show less tendency to stay elongated when the field was removed, a condition observed by H. A. McTaggart(1) and J. K. Robertson(1).

The first specimen used was a nickel wire, the second and third were a bar of invar obtained from Professor Williams of Oberlin College. The invar was first used for a characteristic run in its original size, then turned down to approximately the size of the nickel. The dimensions were as follows:

Specimen	Diameter	Length	Area of Cr.S.
Nickel	1.596 mm.	301.1 mm.	1.9900 sq.mm.
Invar	6.300 mm.	601.0 mm.	31.1725 sq.mm.
Invar	1.602 mm.	269.4 mm.	2.0156 sq.mm.

The lever system for the trial using nickel magnified 560 times, making one millimeter as read equivalent to 17.85 times 10^{-4} mm. elongation (actual). The magnification for invar was

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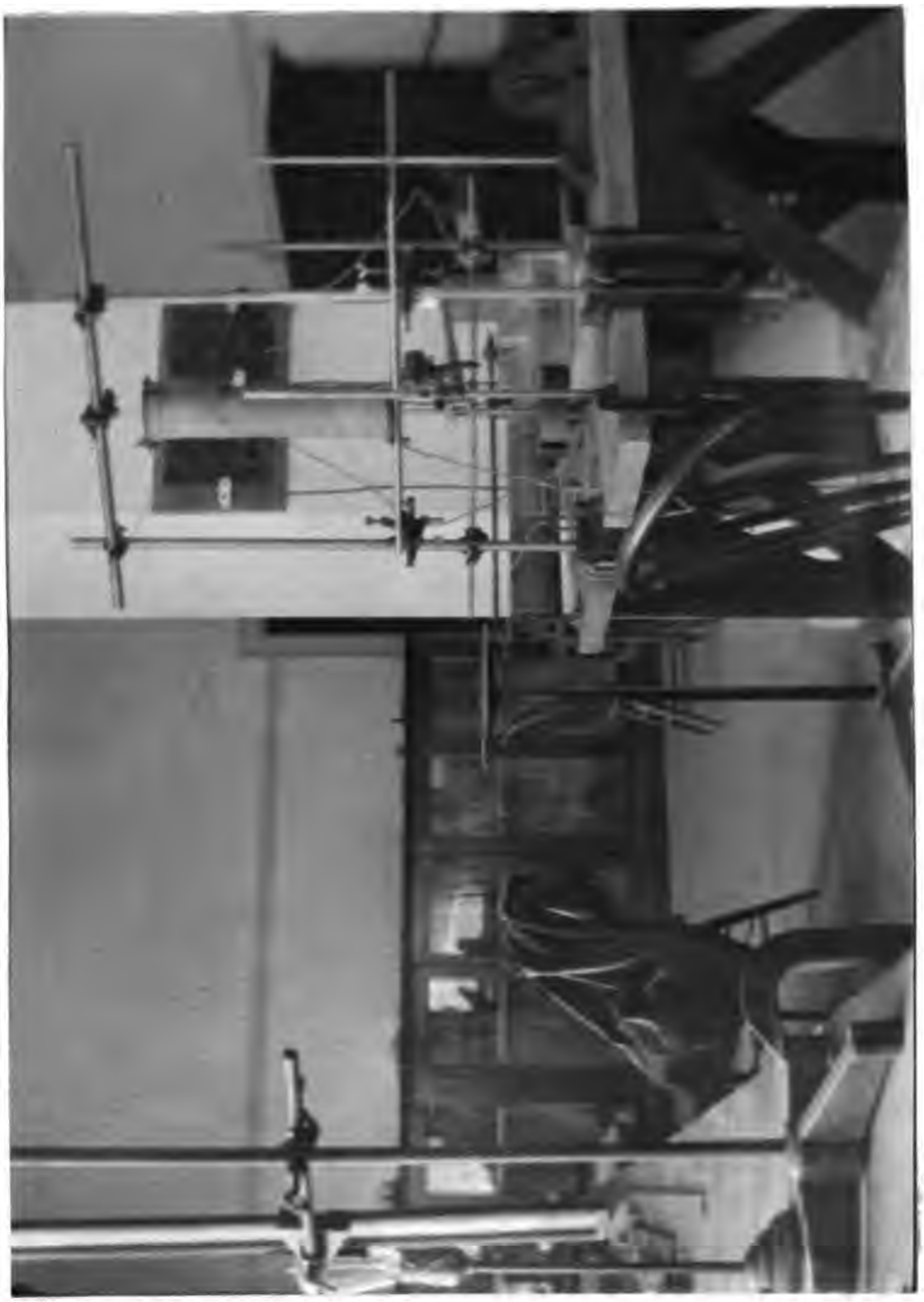
(1) Physical Review, Vol.24, p 458.



1040 times or one millimeter as read was equivalent to 9.614 times 10^{-4} mm. actual elongation.

To discover the nature of the magnetic effect a few sets of readings were taken with decreasing fields immediately after working with increasing fields. The results were smaller deflections than with rising currents, this lagging seemed to be an hysteresis effect, and has also been noted by J. C. McLennan(1).

The change of length of nickel as given by the following tables is shown better by the curves of Graph I at the end of this article. H is the field expressed in gausses, δ the deflection read, and $\frac{\delta l}{l}$ the relation of the actual elongations to the length of the specimen.

DATA FOR NICKEL SPECIMEN.

1. Load 1113.7 gm. Tension 560 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	-0.8	- 4.75 times 10^{-6}
35.41	-2.0	-11.87
70.82	-3.3	-19.58
106.23	-4.0	-23.68
177.05	-4.9	-29.04
247.87	-5.1	-30.17
354.10	-5.2	-30.82
485.12	-5.9	-35.00
531.15	-5.9	-35.00

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(1) Physical Review, Vol.24, p 449.

2. Load 1613.7 gm. Tension 811 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	-0.6	- 3.56 times 10^{-6}
35.41	-1.7	-10.70
70.82	-3.3	-19.80
219.54	-5.2	-30.88
292.13	-5.3	-31.40
371.80	-5.8	-34.90
531.15	-5.9	-34.90

3. Load 2113.7 gm. Tension 1061 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	-0.90	- 5.34 times 10^{-6}
35.41	-2.10	-12.40
70.82	-3.70	-19.80
106.23	-4.96	-29.40
282.20	-5.90	-35.10
354.10	-6.10	-35.95
531.15	-6.30	-36.88

4. Load 3113.7 gm. Tension 1565 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	-1.00	- 5.93 times 10^{-6}
35.41	-2.00	-11.88
70.82	-4.10	-24.40
184.13	-6.00	-35.60
283.28	-6.48	-38.41
389.51	-6.10	-38.20

5. Load 4113.7 gm. Tension 2060 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	-0.70	- 3.957 times 10^{-6}
35.41	-1.80	-10.69
88.52	-4.10	-24.37
223.08	-5.00	-29.70
354.10	-6.50	-38.58
442.62	-6.35	-37.65
531.15	-6.30	-37.38

6. Load 5113.7 gm. Tension 2575 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	-0.20	- 1.18 times 10^{-6}
35.41	-1.45	- 8.55
70.82	-3.25	-19.30
246.09	-6.20	-36.80
354.10	-6.90	-40.90
531.15	-6.95	-41.20

7. Load 8113.7 gm. Tension 4075 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	-0.55	- 3.22 times 10^{-6}
35.41	-1.55	- 9.18
70.82	-3.20	-18.95
212.46	-5.75	-34.05
354.10	-6.15	-36.50
531.15	-6.60	-39.09

8. Load 12,050 gm. Tension 6050 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
35.41	- 2.50	-14.82 times 10^{-6}
70.82	- 5.20	-29.61
106.23	- 7.80	-46.35
177.05	- 9.30	-55.20
354.10	-12.20	-72.50
531.15	-11.80	-70.09

9. Load 18,050 gm. Tension 9080 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
35.41	- 1.25	- 7.11 times 10^{-6}
70.82	- 4.00	-23.75
106.23	- 6.70	-39.80
177.05	-10.00	-59.30
354.10	-12.20	-72.50
531.15	-12.30	-72.80

Graphs number I and III show the tendencies of nickel under tension to elongate rapidly in low fields and more slowly in high fields. The elongation is most rapid for low fields with large tension. Number II is an enlargement of the first part of number I showing the similarity of the curves in low fields.

For the intermediate values of tension a positive value of δ was often obtained for the field of 17.70 gausses for the first one to three readings, then for all further readings for

the same field the elongation was replaced by a contraction. This may be due to impurities in the specimen or to the system adjusting itself when disturbed by the action of the field.

The large invar rod showed the rapid and continual increase shown by Graph number IV, plotted from the following data:

DATA FOR LARGE INVAR ROD.

1. Load 5177.6 gm. Tension 166.3 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	0.30	0.891 times 10^{-6}
35.41	1.00	2.960
70.82	2.10	6.230
157.05	4.00	11.880
283.28	4.60	13.660
393.05	5.10	15.140
531.15	5.25	15.590

With the smaller diameter the invar showed higher points of inflection for $\frac{\delta l}{l}$, although the field at these points did not vary greatly as shown by Graphs V and VI. For smaller values of the load the inflection was sharpest, and the other sharp turns occurred under high tension. Under the latter condition the value of $\frac{\delta l}{l}$ decreased with the load. From the tendency of the curves for loads of 1113.7 gm., 8113.7 gm., and 15,050 gm., it would seem that all the deflections would begin to decrease at some point if the field were sufficiently large.

Graphs V and VI show the tendencies of the following observations:

1. Load 1113.7 gm. Tension 552.5 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	0.60	2.14 times 10^{-6}
35.41	1.55	5.50
106.23	4.35	15.56
177.05	5.65	20.18
266.00	5.70	20.39
425.50	4.40	15.70
532.00	3.90	13.88

2. Load 3113.7 gm. Tension 1543 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	1.00	3.56 times 10^{-6}
35.41	2.00	7.12
106.23	4.05	14.60
177.20	4.90	17.49
248.00	5.30	18.89
354.10	5.90	20.98
425.50	6.50	23.20
532.00	6.30	22.50

3. Load 4113.7 gm. Tension 2041 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	0.90	3.574 times 10^{-6}
35.41	2.00	7.14
70.82	3.25	11.78
106.23	4.10	14.59
177.05	4.90	17.50
283.28	5.30	18.92
354.10	5.45	19.62
532.00	5.95	21.40

4. Load 5113.7 gm. Tension 2541 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	0.85	3.03 times 10^{-6}
35.41	1.50	5.34
70.82	3.00	10.71
106.23	3.70	13.20
177.05	4.50	16.07
247.87	5.50	19.62
389.51	5.80	20.70
532.00	6.10	21.78

5. Load 8113.7 gm. Tension 4028 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	0.90	3.92 times 10^{-6}
35.41	1.60	5.71
70.82	2.60	9.27
106.23	3.10	11.08
177.05	4.10	14.61
247.87	4.20	15.00
389.51	5.00	17.89
532.00	5.20	18.50

6. Load 15,050 gm. Tension 7460 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
17.70	0.35	1.06 times 10^{-6}
35.41	1.20	5.355
70.82	2.25	8.21
106.23	2.80	10.00
177.05	3.00	10.73
354.10	3.10	11.08
531.15	3.00	10.73

7. Load 18,050 gm. Tension 8965 gm./sq.mm.

H (gausses)	δ (mm.)	$\frac{\delta l}{l}$
35.41	1.00	3.57 times 10^{-6}
70.82	1.40	5.01
106.23	1.65	5.72
177.05	1.70	6.08
354.10	2.10	7.15
531.15	2.20	7.85

Graph VII shows a comparison of invar and nickel under the same fields with tensions of 2041 gm. per square mm. and 2060 gm. per square mm., respectively. The magnetostrictive effects are in general quite similar for the two materials but the changes are opposite in sign which means that invar has a continual elongation, whereas nickel always contracts, and the contraction of the nickel has nearly twice the value of the expansion of the invar.

From the data and calculations already given, an interpolation was made giving $\frac{\delta l}{l}$ as a function of tension expressed in grams per square millimeter with the fields of the graphs increasing from 17.70 gausses to 531.15 gausses. The rearranged data which follows supplied the material for Graph VIII.

T- $\frac{\delta l}{l}$ DATA FOR NICKEL ONLY

Tension in gm./sq.mm.	$\frac{\delta l}{l}$ for H = 17.70 gausses	$\frac{\delta l}{l}$ for H = 35.41 gausses	$\frac{\delta l}{l}$ for H = 70.82 gausses	$\frac{\delta l}{l}$ for H = 106.23 gausses
560	-4.750×10^{-6}	-11.87×10^{-6}	-19.58×10^{-6}	-23.68×10^{-6}
811	-3.560	-10.70	-19.80	-25.95
1061	-5.340	-12.40	-19.80	-29.40
1565	-5.950	-11.88	-24.40	-30.40
2060	-3.957	-10.69	-24.50	-30.05
2575	-1.180	- 8.55	-19.30	-25.70
4075	-3.220	- 9.18	-18.95	-25.65
6050	-5.450	-14.82	-29.61	-46.35
9080	-2.300	- 7.11	-23.75	-39.80

$T-\frac{\delta l}{l}$ DATA FOR NICKEL ONLY--(concluded).

Tension in gm./sq.mm.	$\frac{\delta l}{l}$ for H = 177.05 gausses	$\frac{\delta l}{l}$ for H = 354.1 gausses	$\frac{\delta l}{l}$ for H = 531.15 gausses
560	-29.04×10^{-6}	-30.82×10^{-6}	-35.00×10^{-6}
811	-27.80	-33.10	-34.90
1061	-32.95	-35.95	-36.88
1565	-32.80	-37.70	-38.60
2060	-35.60	-37.65	-37.38
2575	-33.20	-40.90	-41.20
4075	-32.50	-36.50	-39.09
6050	-55.20	-72.50	-70.09
9080	-59.30	-72.50	-72.80

The pronounced similarity of the curves of Graph VIII show that in all fields used the nickel tends to shorten under low tension and to decrease the amount of contraction at higher tensions until a maximum point is reached after which the specimen again contracts toward a point of minimum length. The low fields seem to signify that a minimum point is reached at higher tensions than those used, which is followed by another decrease of contraction.

$T - \frac{\delta l}{l}$ DATA FOR INVAR ONLY

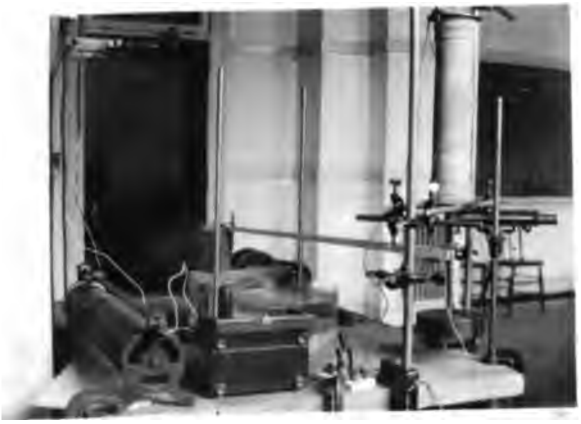
Tension in gm./sq.mm.	$\frac{\delta l}{l}$ for $H = 17.70$ gausses	$\frac{\delta l}{l}$ for $H = 35.41$ gausses	$\frac{\delta l}{l}$ for $H = 70.82$ gausses	$\frac{\delta l}{l}$ for $H = 106.23$ gausses
552.5	2.140×10^{-6}	5.500×10^{-6}	11.88×10^{-6}	15.56×10^{-6}
1543.0	3.560	7.120	11.78	14.60
2041.0	3.574	7.140	-----	14.59
2541.0	4.270	5.340	10.71	13.20
4028.0	3.920	5.710	9.27	11.08
7460.0	1.060	5.355	8.21	10.00
8965.0	-----	3.570	5.01	5.72

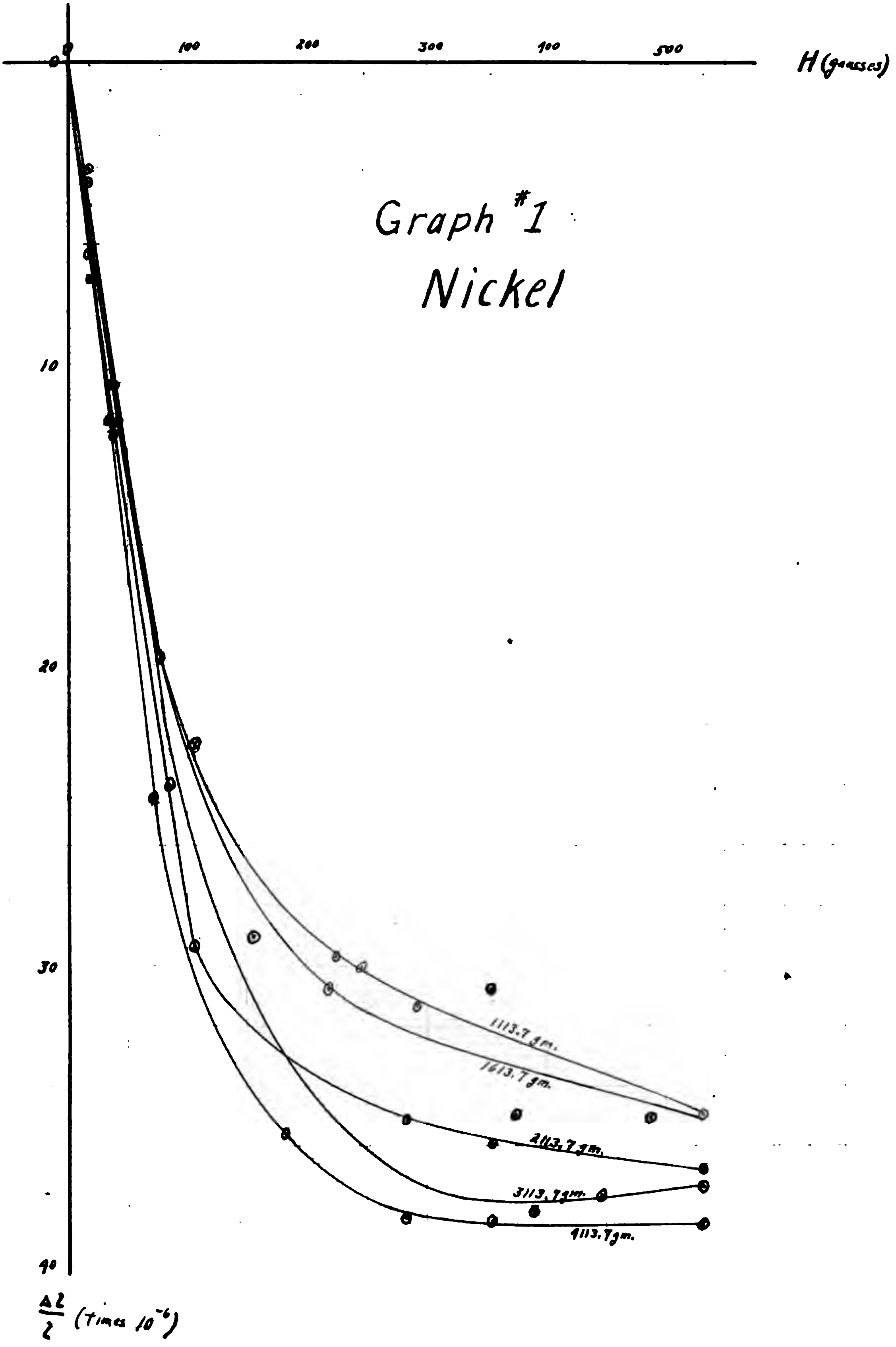
T- $\frac{\delta l}{l}$ DATA FOR INVAR ONLY------(concluded).

Tension in gm./sq.mm.	$\frac{\delta l}{l}$ for H = 177.05 gausses	$\frac{\delta l}{l}$ for H - 248.00 gausses	$\frac{\delta l}{l}$ for H = 354.10 gausses	$\frac{\delta l}{l}$ for H = 531.15 gausses
552.5	20.18 x 10^{-6}	20.60 x 10^{-6}	17.40 x 10^{-6}	13.88 x 10^{-6}
1543.0	17.49	18.89	20.98	22.50
2041.0	17.50	19.05	19.62	21.40
2541.0	16.07	19.62	20.38	21.78
4028.0	14.61	15.00	17.60	18.50
7460.0	10.73	10.95	11.08	10.73
8965.0	6.08	6.63	7.15	7.85

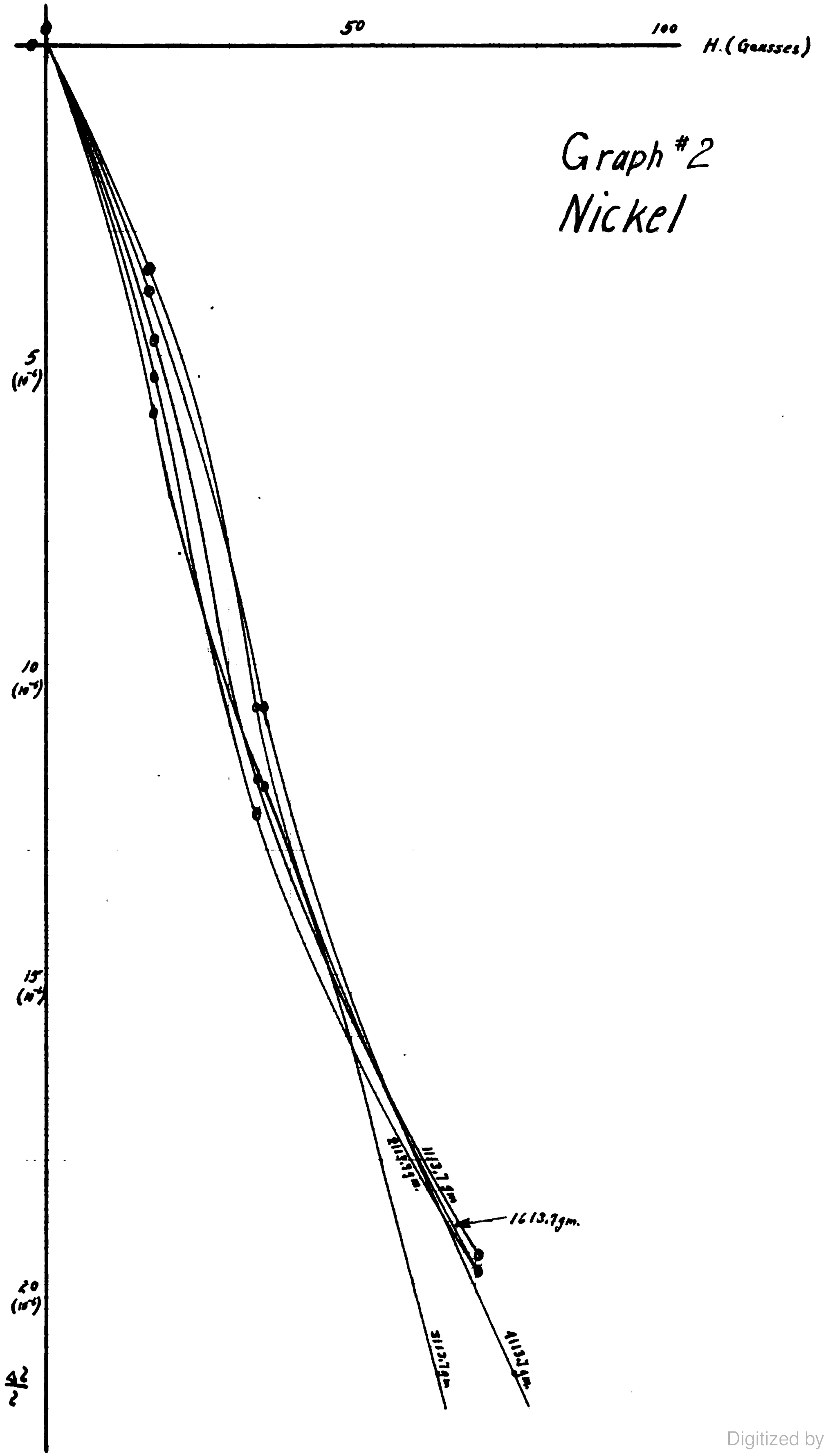
The preceeding data for invar shows on Graph IX the maximum elongation at low tension with a decrease under increasing tension while approaching the axis of tension. Honda found that the curves for several metals approached the tension axis asymptotically at higher tensions.

The results obtained are very much like those obtained by persons, among them Honda, Nagaoka, Shimizu, Williams, and McLennan, who have studied the elongation effect of magnetic fields.

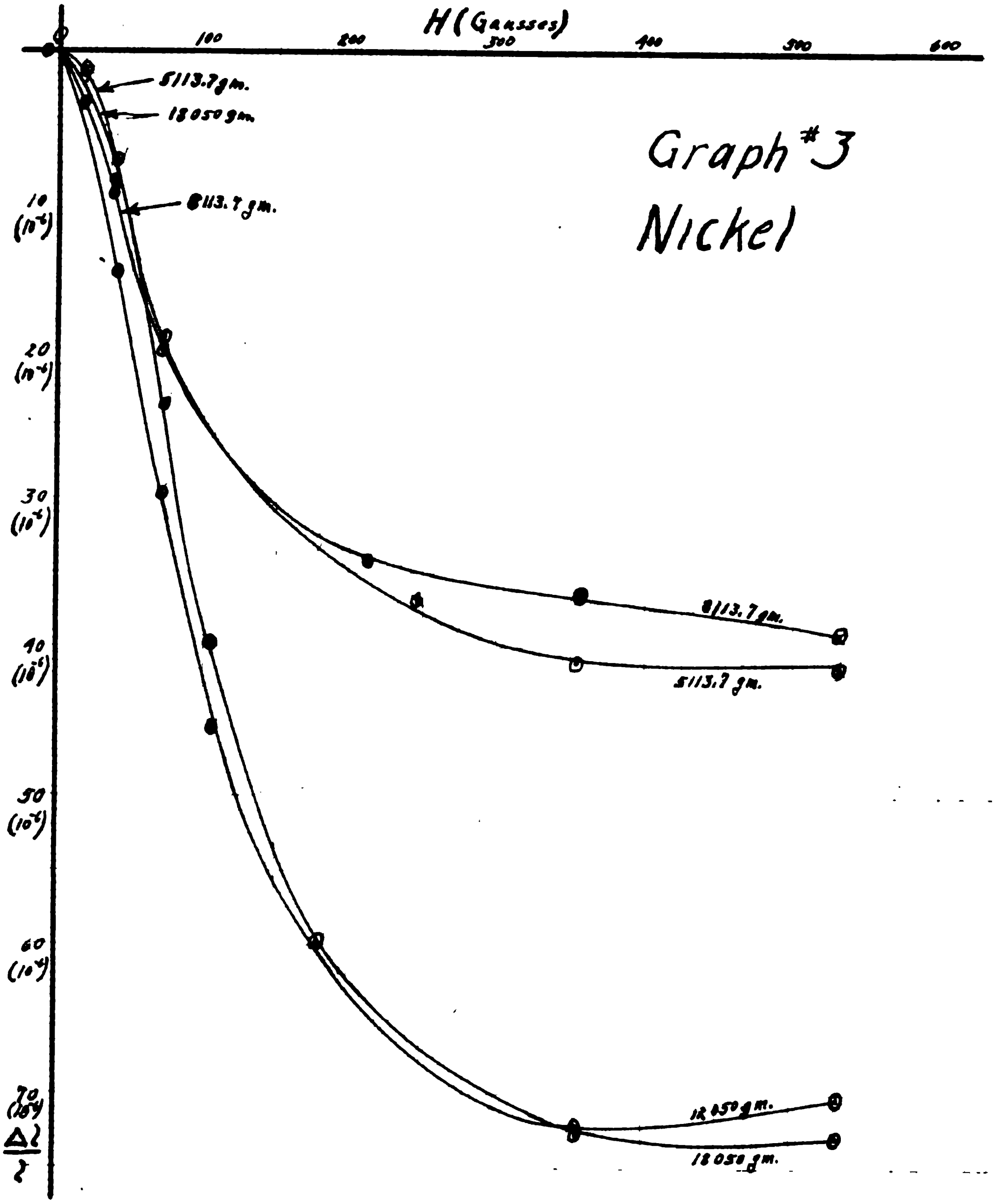



Graph #1
Nickel
0
100
200
300
400
500
H (gausses)
10
20
30
40
Δl/l (times 10⁻⁶)
1113.7 gm.
1613.7 gm.
2113.7 gm.
3113.7 gm.
4113.7 gm.

FORM C1



Graph #2
Nickel

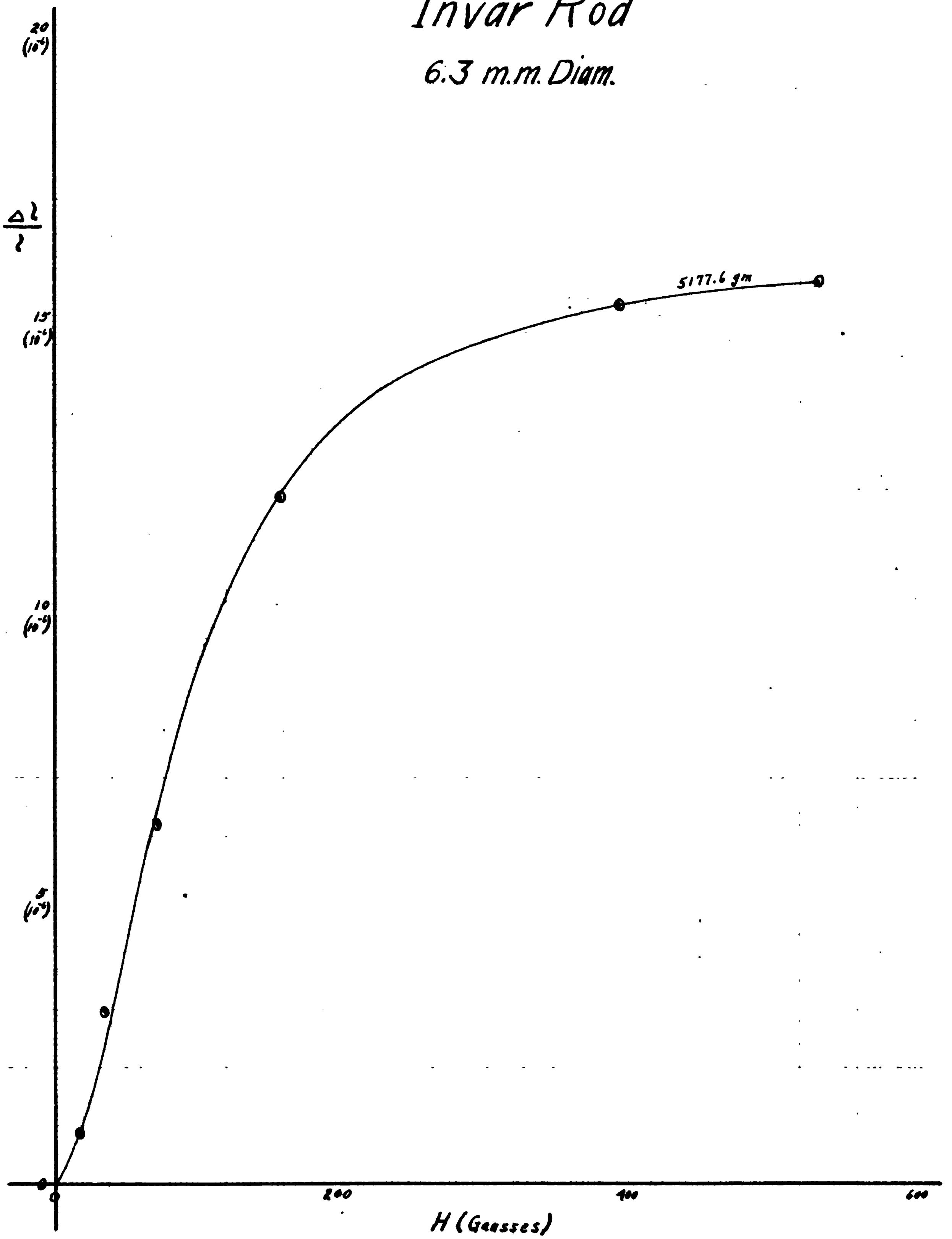


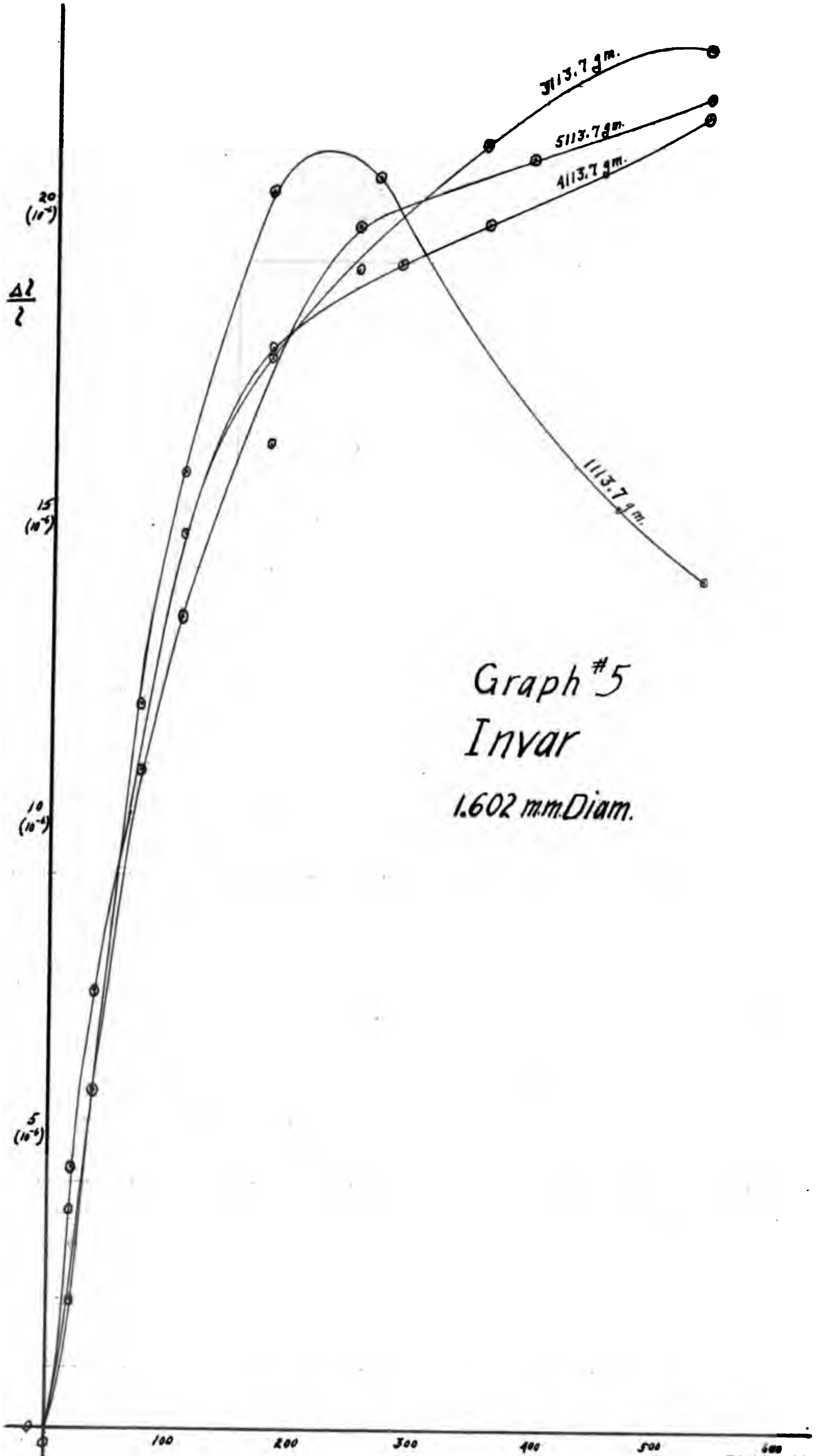
Graph #3
Nickel

Graph #4

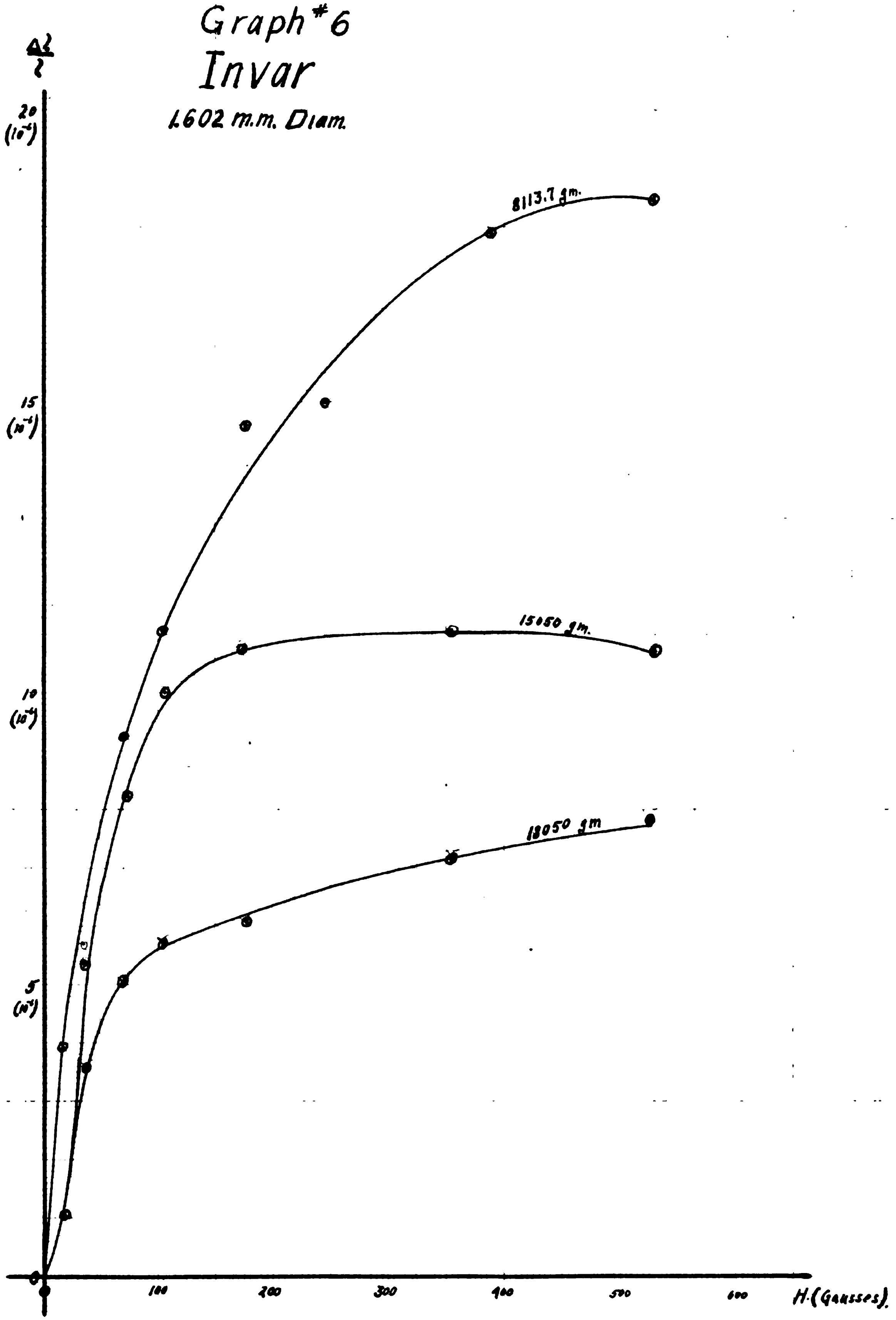
Invar Rod

6.3 m.m. Diam.



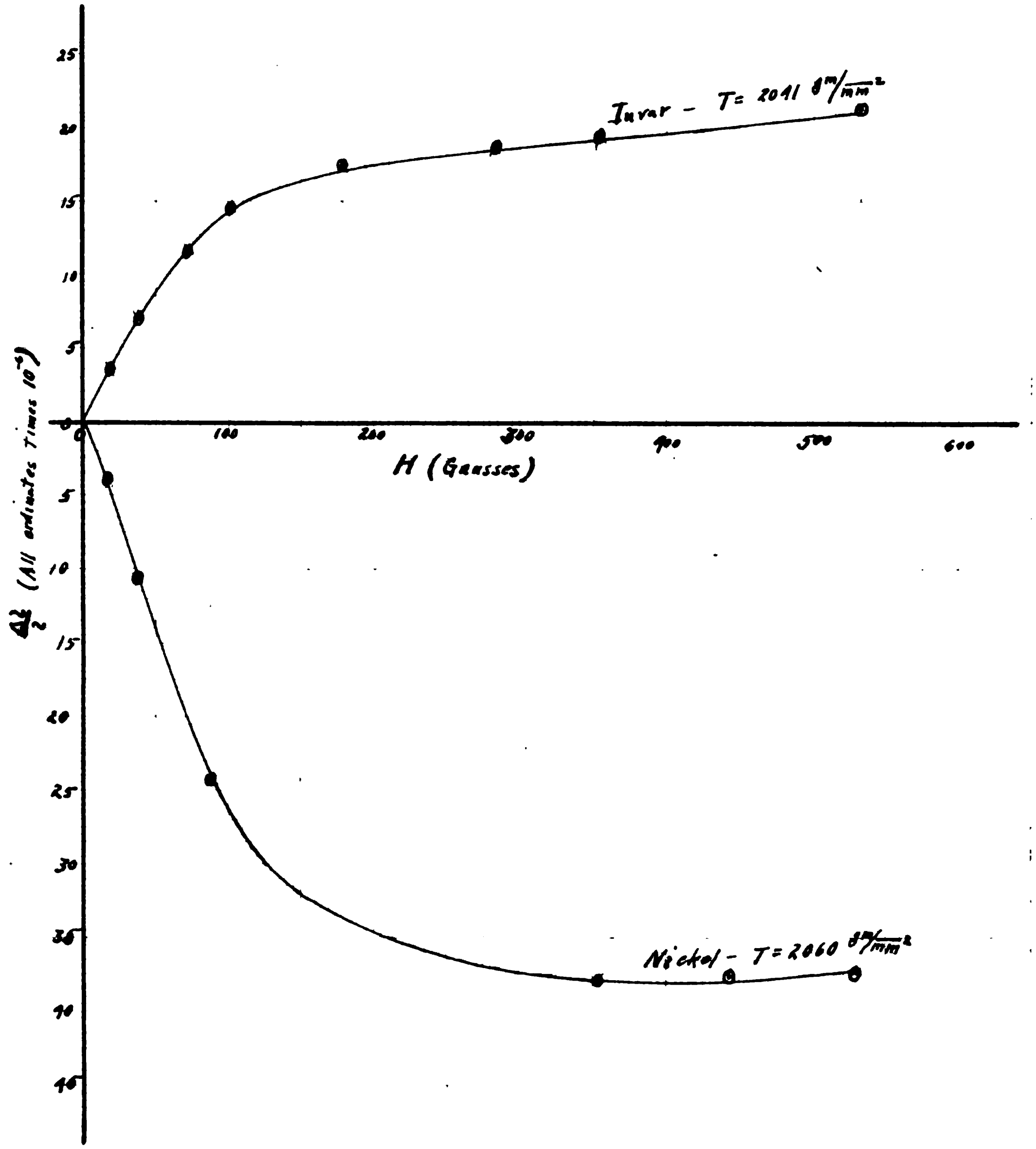


Graph #5
Invar
1.602 mm. Diam.



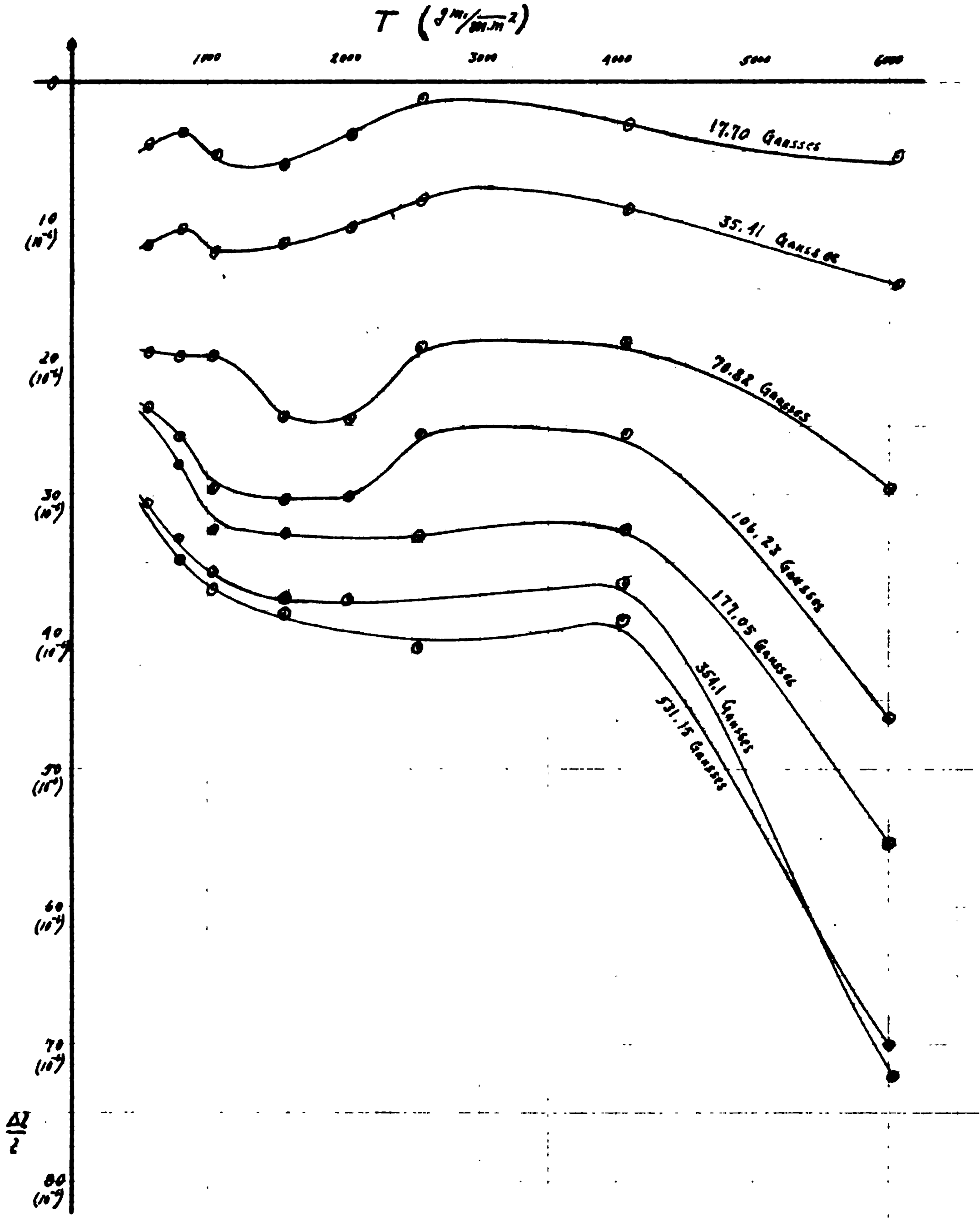
Graph #6
Invar
1.602 m.m. Diam.

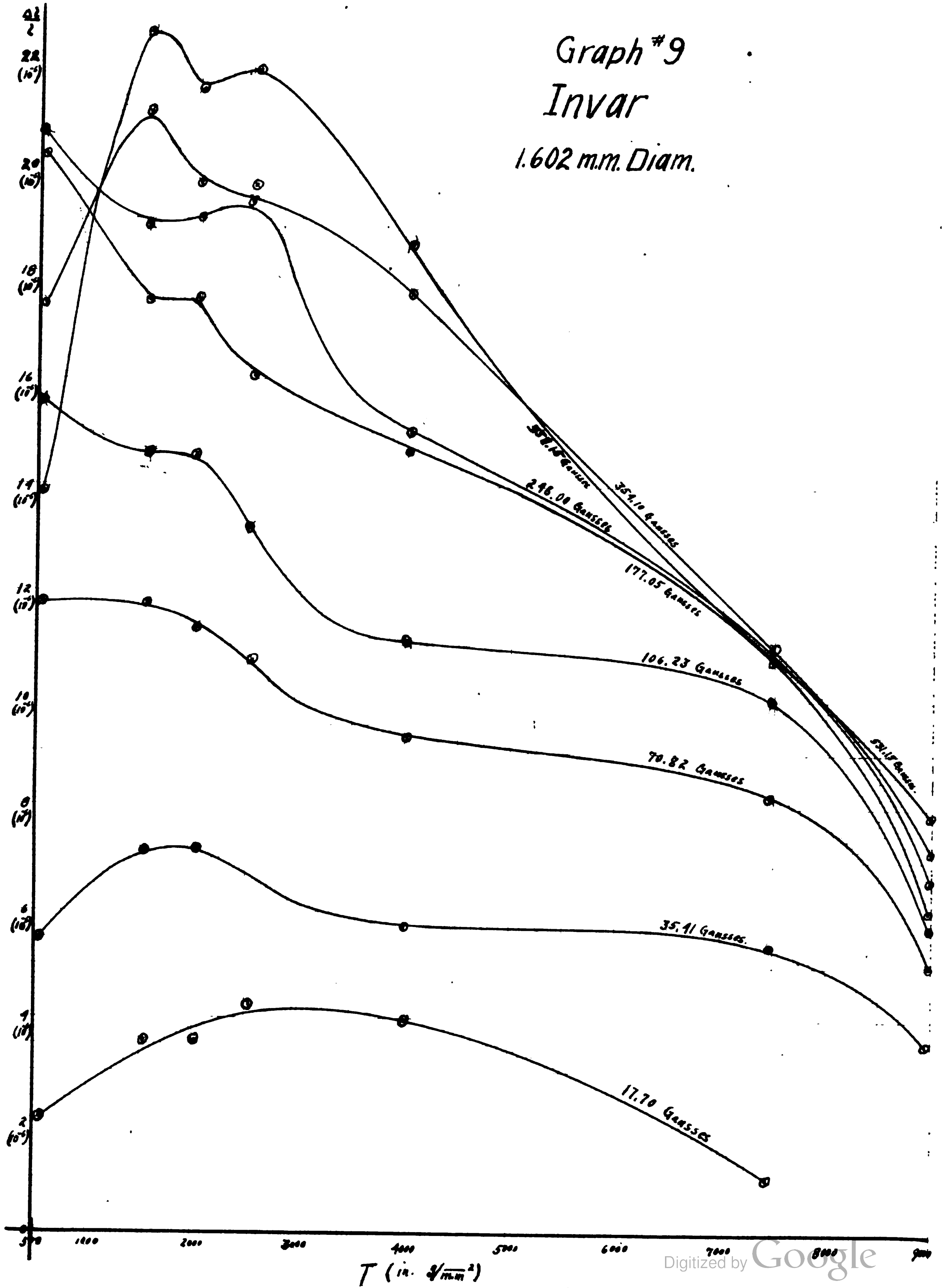
Graph # 7
Comparison
of
Invar & Nickel



Graph #8

Nickel





Graph #9
Invar
1.602 m.m. Diam.

APPROVED

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Associate Professor of Physics

March 21 1922

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